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AN EXTREMELY WIDE BANDWIDTH, LOW-NOISE SIS HETERODYNE RECEIVER DESIGN FOR MILLIMETER AND SUBMILLIMETER OBSERVATIONS

Matthew Sumner[1], Andrew Blain[2], Andrew Harris[3], Robert Hu[4], Frank Rice[1], H. G. LeDuc, Sander Weinreb[5], Jonas Zmuidzinas[1]

[1]California Institute of Technology, MS 320-47, Pasadena, CA 91125
[2]California Institute of Technology, MS 105-24, Pasadena, CA 91125
[3]Department of Astronomy, University of Maryland, College Park, Maryland 20742
[4]University of Michigan, c/o Caltech, MS 320-47, Pasadena, CA 91125
[5]Jet Propulsion Laboratory, MS 168-214, Pasadena, CA 91109

ABSTRACT

Millimeter and submillimeter heterodyne receivers using state-of-the-art SIS detectors are capable of extremely large instantaneous bandwidths with noise temperatures within a few Kelvin of the quantum limit. We present the design for a broadband, sensitive, heterodyne spectrometer under development for the Caltech Submillimeter Observatory (CSO). The 180 – 300 GHz double-sideband design uses a single SIS device excited by a full bandwidth, fixed-tuned waveguide probe on a silicon substrate. The IF output frequency (limited by the MMIC low noise IF preamplifier) is 6 – 18 GHz, providing an instantaneous RF bandwidth of 24 GHz (double-sideband). The SIS mixer conversion loss should be no more than 1 – 2 dB with mixer noise temperatures across the band within 10 Kelvin of the quantum limit. The single-sideband receiver noise temperature goal is 70 Kelvin.

The wide instantaneous bandwidth and low noise will result in an instrument capable of a variety of important astrophysical observations beyond the capabilities of current instruments. Lab testing of the receiver will begin in the summer of 2002, and the first use on the CSO should occur in the spring of 2003.

INTRODUCTION

The current generation of heterodyne receivers in use on major telescopes in the 180 – 300 GHz range typically offer an IF bandwidth of a few GHz, although some recent designs have pushed that limit to 8 GHz.[1] Extending this bandwidth even further would be highly desirable, as several applications have recently come to light that would benefit greatly from this improvement.

Surveys using submillimeter cameras (such as SCUBA and MAMBO) have resulted in the discovery of roughly 200 very luminous galaxies. These sources appear to be at high redshifts, although only a handful have been precisely measured.[2] In principle, the distance can be determined using spectral lines from several molecules (particularly CO) that can be observed in the submillimeter band; however, because of the high redshifts of these objects, a large fraction of the 190 – 320 GHz atmospheric window must be searched to find these lines. Since these are such faint sources, each observation requires several, or even tens, of hours per LO frequency, even with a sensitive receiver. Therefore, in order to build up a statistical sample of the redshifts of these objects, a high-bandwidth receiver is required.

In the Earth Sciences community, this type of receiver would be very useful for studying the Earth's atmosphere. The atmospheric abundances of several important molecules can be mapped by detecting their spectral-line emissions at submillimeter wavelengths (near 230 GHz). Two generations of satellites have been built that use this technique to provide considerable information on atmospheric chemistry, ozone depletion, and the global effects of pollution.[3] As the next step in this research, a new satellite mission, the Scanning Microwave Limb Sounder (SMLS), has been proposed that would provide many more data points, allowing for higher resolution and better coverage. A receiver with a large bandwidth and low noise is required to allow the satellite to measure multiple spectral lines accurately with a single pointing of the antenna.

Contact information for Matthew Sumner: sumner@caltech.edu (email) or (626) 395-4246 (phone)

RECEIVER DESIGN

In order to address some of these needs, we have developed a new receiver design with an eye toward maximizing the bandwidth while maintaining the low noise temperature required for these measurements. Our initial design consists of a double-sideband receiver using a single SIS mixer. Intensive simulations, combined with preliminary measurements, indicate that the design will offer a 12 GHz IF bandwidth (6 – 18 GHz), corresponding to a double-sideband RF bandwidth of 24 GHz, while maintaining a noise temperature that is competitive with other narrower bandwidth designs.

Mixer Circuit Design

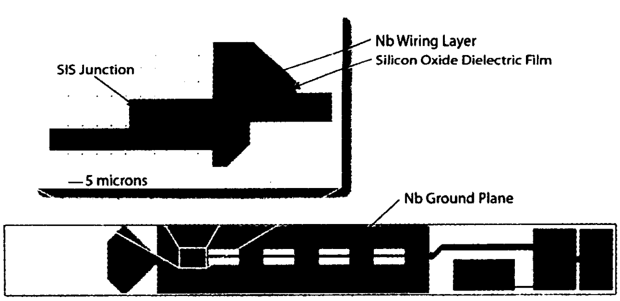
The heart of the RF mixer is an Nb-AlN-Nb SIS junction. The 1.3×1.3 micron junction will have a critical current density (J_c) of 14 kA/cm^2, resulting in a normal resistance (R_n) of 8.5 Ω and a junction capacitance of 144 fF. The junction size is suitable for UV contact lithography, and the R_n×C product corresponds to a frequency of 130 GHz. Current technology at JPL can produce such junctions with very high quality, so a subgap-to-normal resistance ratio in excess of 20 should be easily attainable.

The SIS junction is coupled to the waveguide probe using a thin-film, superconducting microstrip matching network consisting of a ¼-wave transformer followed by a two-section LC ladder (see Figure 1-a). The RF network tunes out the SIS junction capacitance and matches the 36 Ω probe to the 9 Ω junction impedance. The IF output is extracted from the low impedance, fan end of the large radial-stub capacitor.

The IF output then passes through a CPW/microstrip filter ladder that provides RF isolation and matches the junction to the 50 Ω IF load. The IF signal is coupled to the preamplifier via a DC blocking capacitor just before IF wirebond pad at the right side of Figure 1-a. DC bias for the SIS junction is provided through the wirebond pad to the left of the DC blocking capacitor.

The niobium ground plane is 0.2 microns thick, and the wiring thickness is 0.4 microns. The conductors are separated by a 0.35 micron thick SiO layer. The layout is suitable for UV contact lithography and uses a minimum wire width of 3.0 microns in the RF section. The ground plane extends just to the waveguide wall and is shorted to the waveguide block along each edge of the substrate using thick gold pads which contact the upper half of the split waveguide block when the block is assembled.

The entire circuit has been modeled and optimized by C++ programs using the *SuperMix* library. Figure 1-b shows the modeled performance of the optimized mixer chip design. Clearly, powerful software tools like *SuperMix* and *Ansoft HFSS* can improve the performance and lower the technical risk of current design efforts.



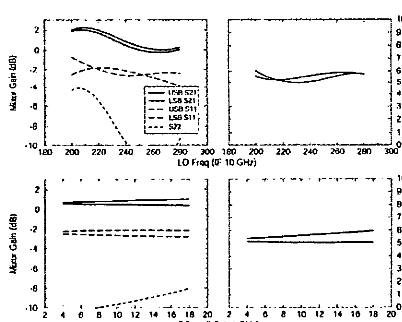
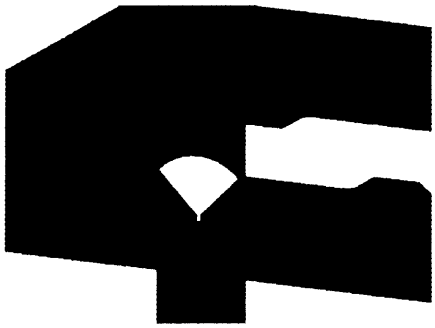


Figure 1-a *(left)*: Preliminary mask layout for the SIS mixer chip. The broadband radial-stub probe (at left) couples the signal from the waveguide into the RF matching network (shown in the enlargement). The IF output is picked off from the low-impedance, outer edge of the radial-stub capacitor (at the right side of the inset). The IF signal then travels through a CPW/microstrip filter ladder (for RF isolation) to the bonding pad at the far right end of the chip. DC bias is provided through the bonding pad just to the left of the large DC blocking capacitor.

Figure 1-b *(right)*: Simulated performance of mixer circuit showing the gain and the noise in excess of the quantum limit (which is approximately 10 K at these frequencies). The circuit is expected to achieve a noise temperature less than twice the quantum limit.



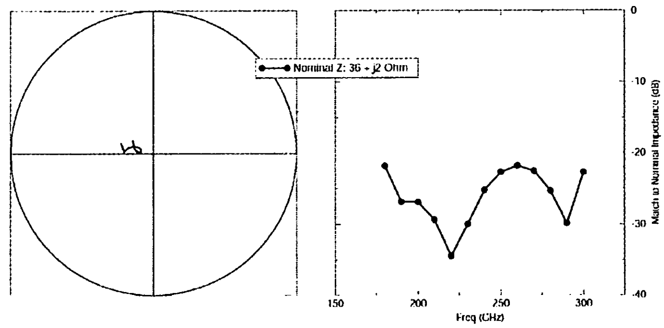


Figure 2-a ***(left)*****:** Broadband probe and mixer chip shown in relation to waveguide (also see Figure 1-a). The faint line indicates the split plane in the mixer block. The small tuning step upstream of the probe and the fixed backshort were optimized using circuit models based on the *SuperMix* library.
Figure 2-b ***(right)*****:** Predicted performance of probe based on *HFSS* model. The probe offers an almost real impedance of (36 + j 2) Ω over the 180 – 300 GHz range of the receiver.

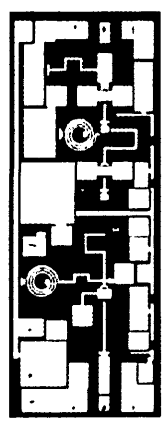
Broadband Probe

The RF signal is coupled to the SIS device through a radial-stub waveguide probe that covers the 180 - 300 GHz operating range of the receiver. As shown Figure 2-b, the probe impedance remains essentially constant over the 1.7:1 frequency range, with a nominal impedance that is very nearly real.

The waveguide includes a fixed backshort and a small capacitive tuning step just upstream of the probe (Figure 2-a). The configuration was designed by first modeling the individual components in *Ansoft HFSS* and importing their behaviors into a C++ circuit model based on the *SuperMix* library, which was used to optimize the backshort and tuning step. The results shown were generated from an *HFSS* model of the entire probe and waveguide structure. These results have been validated for a very similar design by comparing the *HFSS* results to scale-model measurements.

Cryogenic Low-Noise Preamplifier

The IF output of the mixer must be amplified using a low noise preamplifier with bandwidth and noise characteristics that will not compromise the overall performance of the receiver. Microwave monolithic integrated circuit (MMIC) technology employing indium phosphide (InP) high electron mobility transfer (HEMT) active elements has been identified as the most promising route to achieving these goals. We are currently refining a design based on the TRW WBA8T MMIC, which uses a 75 micron thick substrate with four 150-micron InP HEMT stages (Figure 3-a). The latest iteration of this design uses inductive feedback to minimize noise, and preliminary measurements indicate that it offers 20+ dB of gain with a noise temperature below 10 K from 6 to 10 GHz (Figure 3-b). These measurements are consistent with simulations that predict similar performance across the entire 6 – 18 GHz IF band of the receiver.



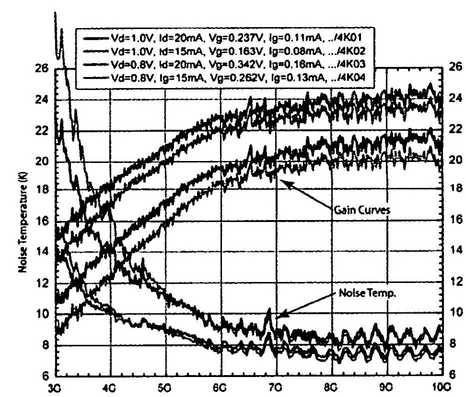


Figure 3-a ***(left)***: Picture of the IF preamplifier circuit. This version, based on the TRW WBA8T MMIC, uses inductive feedback to minimize noise.
Figure 3-b ***(right)***: Preliminary measurements of the preamplifier's performance at 4 K. These measurements are consistent with simulations predicting that the preamplifier will achieve 20+ dB of gain with less than 10 K noise temperature over the 6 – 18 GHz IF band of the receiver. (The limited frequency range, as well as the "ripple" that can be seen in the data, are limitations of the test setup and will be corrected in future measurements.)

Final IF Amplifier

The final stage of the receiver is an amplifier that can be used at room temperature or at 77 K. The design uses three commercial MMIC amplifiers. The amplifier has been designed, built, and tested, and results are shown for the 2 – 20 GHz band (Figure 4). It can achieve a 30 dB gain, with less than 3 dB variation, over the entire IF bandwidth of the receiver.

WASP2 Spectrometer

For astrophysical observations at the CSO, the receiver will be used with the WASP2 spectrometer to search for spectral lines from submillimeter sources that have been observed by the SCUBA instrument. WASP2 is a wideband lag correlation spectrometer being developed at the University of Maryland that can cover a 3.6 GHz bandwidth.[4] By combining several of these instruments, we will be able to utilize the entire 12 GHz bandwidth of the receiver.

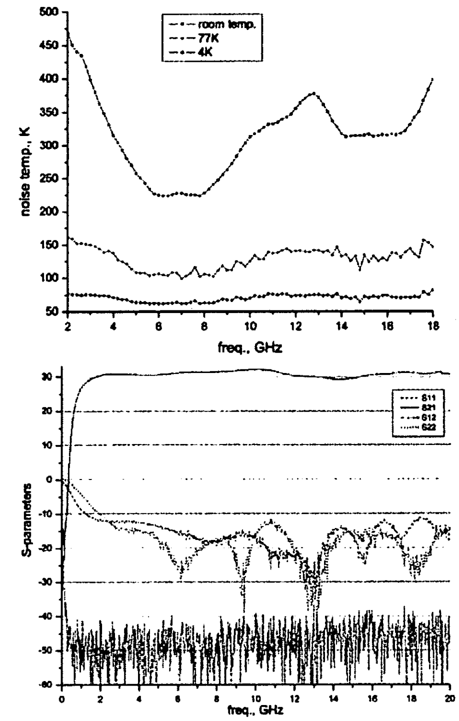


Figure 4: Measured performance of room-temperature IF amplifier. The design offers low-noise (top) and a 30 dB gain (bottom) across the IF bandwidth of the receiver.

SUPERMIX

The design of this receiver has relied heavily on the use of *SuperMix*, a software package developed at Caltech that provides a complete set of circuit elements suitable for frequency-domain simulations from DC to THz. The library allows for accurate modeling of superconducting transmission line elements and predicts the nonlinear SIS mixing performance using Tucker's quantum mixing theory. In addition, the *SuperMix* package includes a sophisticated multi-parameter optimizer that can be used to refine a circuit design by modifying any device characteristics. For more information, visit *http://www.submm.caltech.edu/supermix*.

SUMMARY

We present the design for a low-noise submillimeter receiver that has been optimized to provide a wide IF bandwidth (6 – 18 GHz) in the 180 – 300 GHz range. The initial design consists of a double-sideband receiver that will offer an instantaneous RF bandwidth of 24 GHz, with a single-sideband receiver noise temperature goal of 70 Kelvin. Already, some elements have been built, and lab testing of the full receiver should begin in a few months. Starting in the spring of 2003, we plan to use the receiver at the CSO to study CO spectral lines from the submillimeter sources discovered by SCUBA. Eventually, these measurements should allow us to produce much-needed redshift determinations for these objects.

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